Methods for evaluating risk caused by ice throw and ice fall from wind turbines and other tall structures

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***Abstract*:**

IceRisk, a state-of-the-art method for assessing site specific risk caused by ice fall or throw from turbines or other tall structures, has been developed in close collaboration between Kjeller Vindteknikk and Lloyd's Register Consulting. The method consists of a detailed meteorological simulation resulting in maps of ice throw probability zones and safety distances for the considered site, followed by a risk assessment. The approach results in a map showing safety zones, i.e. what type of activities are acceptable within the vicinity of the wind turbine or similar installation.

Guidelines for acceptable risk levels, both for facility operating personnel and for third parties, are proposed. The calculated risk for any specific site may take into account local risk reducing measures, and calculate individual risk for different exposure, such as pedestrians and vehicle passengers, separately.

The IceRisk methodology has so far been applied for met masts, tall towers, power lines and wind turbines in Norway. Since 2013, validation work has been performed by ongoing inspections on and around a 209 m telecom mast at Tryvann, Oslo.

Keywords: IceRisk, ice throw, ice fall, turbines, telecom masts, power lines, wet snow icing, rime ice, risk assessment, risk mitigation, forecast, warning systems .

LEGEND AND ABBREVIATIONS

a	*height of ice piece, e.g.: $(L/rho)^{0.5}$*
b	*width of ice piece*
c	*length of ice piece*
Cd	*Drag coefficient, taken as 1.0*
A	*Effective frontal ice piece area: 0.5*(ab+ac+bc)*
ρ	*Density ice, typical value hard rime: 500 kg/m^3*
ρ_{air}	*Density air, typical value 1.22 kg/m^3*
M	*Mass ice piece: rho*a*b*c*
g	*Gravitational acceleration: 9.81 m/s^2*
CdAoM	*Form factor icefall: Cd*A/M*
Vt	*Terminal velocity: $(2*g/rho\_air/CdAoM)^{0.5}$*
E	*Impact kinetic energy ~ $0.5*M*Vt^2$*
LIRA	*Localized individual risk, Outer safety zone at level <1e-6 [fatalities/year]*
H	*Hub height wind turbine*
D	*Rotor diameter wind turbine*
dZ	*Overheight*
L	*Ice load [kg/m], typically accreted on a rotating vertical cylinder of diameter 30 mm*
DSB	*Norwegian Directorate for Civil protection*

INTRODUCTION

The IceRisk-methodology is used to assess risks associated with being hit by ice pieces shedded from a fixed or moving structure. A typical result is at what distances the risks for being struck by a falling ice debris are acceptable for different exposures such as facility workers, occasional 3rd persons present, or vehicle passengers given none or different considered risk mitigation efforts. The methodology is also suited for assessing the damage potential on structures and property.

The methodology presented in this article is primarily based on a ballistic ice throw model [1] coupled with a detailed meteorological study and a risk assessment as well as our own experiences [2][3][4] and others experiences of ice throw modelling and observed distances of ice throw and ice fall [5][6][7][8][9][10][11].

In this article the IceRisk methodology is presented with results from a selection of our own studies in Norway regarding the associated risk from telecom towers, power lines and wind turbines [2][3][4][21][22][23][25][26][27] .

I. METHODOLOGY

The IceRisk-methodology consists of several parts; First a detailed longterm meteorological modeling of the wind and icing condition at the site is performed. Then the aggregation [13] of ice in the construction is calculated before we consider under which conditions ice pieces are shedded from the construction. E.g. how is the shedding related to melting conditions and/or stronger wind episodes when dangerous amounts of ice are present. An ice fall size distribution is calculated and classified by analyzing the ice amounts that is accreted and shed above associated ice load thresholds. Given the wind conditions with dangerous ice amounts present (e.g. L > 1-2 kg/m) and the size distribution one can use a ballistic trajectory model [1] to calculate the impact position and kinetic energies of the ice pieces (assumed shaped as freely rotating ice cubes). For wind turbines one also has to consider the angular and radial distribution functions for ice throw release positions [6]. Here, we consider ice pieces with impact kinetic energies above 40 J and with weights above 100 g, as dangerous (fatal) [2][4][18]. A combination of the statistics are then performed resulting in probability maps and tables. Finally a risk assessment study is performed yielding the safety zones around the facilities where different exposures are allowed. When risks are above threshold values [2][3][4] one should incorporate risk mitigations efforts if re-siting is not possible. Based on model validation we consider ice fall drift distances calculated with a high degree of accuracy [23].

II. ICE FALL CALCULATIONS

The parameters describing the impact position and velocities for a shed ice piece are the release position, release velocity, wind velocity, wind shear, terrain and combined form parameter C_d*A/M[1]. Here, C_d is the drag coefficient[2], takes as 1.0, while A and M are the effective frontal area for the ice piece (the side oriented against the wind and fall direction) and the mass of the ice piece. If we know the precise form, orientation and weight for an ice piece we can calculate the Cd*A/M parameter to find the associated drift distance and impact kinetic energy for a falling ice piece. The equivalent cross-sectional area for a freely rotating ice cube is 50 % larger than if the ice cube is falling with the smallest face kept oriented against the wind and fall direction. Note that this corresponds to setting an effective drag-coefficient of 1.5 considering the smallest face of the cube as the frontal area. Also note that the combinations of Cd=1 and ρ = 500 kg/m^3, Cd=1.2 and ρ=600 kg/m^3, and Cd=1.4 and ρ=700 kg/m^3 all yield the same form factor Cd *A/M.

A. *Smallest ice piece with kinetic energy above 40 Joule*

Lighter ice pieces drift further than denser ones. From a sensitivity analysis [26] we found that the smallest dangerous ice cube released from 209 m is between 150 and 200 g during calm wind conditions for the respective ice cube densities of 800 and 500 kg/m^3. For 30 m/s wind speeds the lower mass for a freely rotating ice cube is around respectively 100-120 g in the 40 J energy limit for the given densities. Note that these values are valid for ice fall where the terminal velocity is reached from below. For ice throw the terminal velocity is reached from above with time if the initial relative wind velocity is exceeding the terminal velocity.

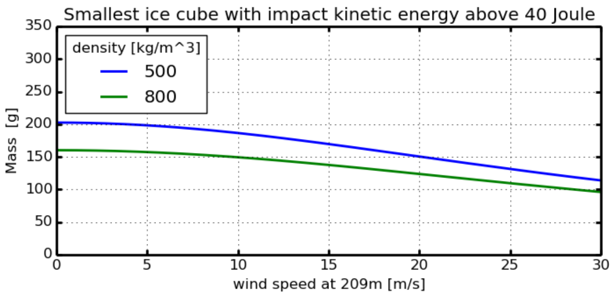

Figure 1 Smallest ice cube at given wind speeds with an impact kinetic energy above 40 J for the respective ice densities of 500 kg/m^3 (blue) and 800 kg/m^3 (green).

B. *Comparison of calculated safety distance for freely rotating ice cube with safety distance rule for stopped turbine*

The safety distance curve for the 40 J ice piece released from 209 m (seen in Figure 14) is nonlinear and can be fitted with the following representation: D = A+B*C*(exp(WS/B)-1). Here WS is the wind velocity at 209 m, A=-3.4, B=63.5, C=8.1, and D is the safety distance. If we compare this safety distance with a general safety rule for a stopped wind turbine: H*vh/15, where H is total height and vh is wind speed at hub height we compare with previous results. With a wind shear of 0.18, a total height of 209, hub height taken as 155 m, and a hub height wind speed of 15 m/s, we get a safety distance of 140 m. This means that the general safety rule distance (209 m for vh=15m/s) can be reduced with 33 % to match our results at this distance.

C. *Sensitivity analysis on form - plates and rods vs ice cubes*

Both freely rotating plates and rods can drift further than cubes in 40 J limit [26]. With wind speeds of 9.5 m/s at 209 m.a.g.l. the horizontal drift distance for ice cubes of density 500 kg/m^3 is 80 m. For plates which are shrunk by a factor 4 on one side the safety distance for the worst size ice plate is approximately 10 m further. For rods a stretch factor of 4 also gives longer drift distances but not as long as for plates.

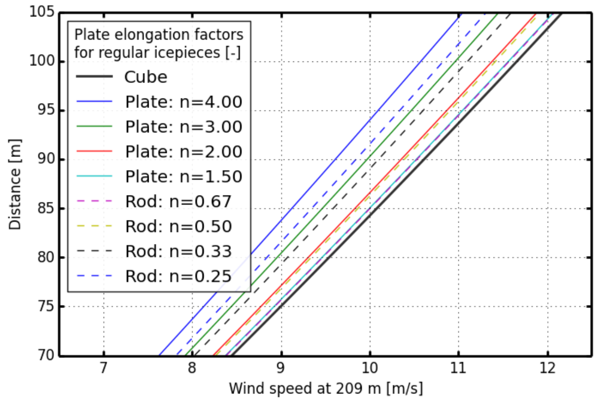

Figure 2: Safety distances for ice cubes with the ratio given in the legend between the height/width and the length of the freely rotating regular ice piece in the 40 J limit.

Calculations with elongation factors above 4 is not shown as the assumption of freely rotating ice pieces might become invalid. At calm wind conditions and a elongation factor of 4 (plate) the ice piece have size of 3.1 x 12.5 x 12.5 cm, weighing 240 gram in the 40 J energy limit. With 35 m/s winds this size is reduced to 2.5 x 9.5 x 9.5 cm with a weight of 110 g. For ice pieces with a density of 800 kg/m^3 the corresponding calm condition size limit is from 2.5 x 10 x 10 cm (190 g) and at 35 m/s the size is 2 x 8 x 8 cm (95 g).

III. ICEFALL FROM THE TRYVANN COMMUNICATION MAST

The IceRisk model is linked to a hindcast archive with time series of meteorological parameters such as icing, wind speed, wind direction and temperature from the 35 year period 1979-2013. For the 209 m tall communication mast at Tryvann [23][26], this archive was used to define the periods of icing and the associated ice amount in the structure.

During the average winter 8 800 kg of ice is shed from the construction (L>1.0 kg/m). 4 200 kg of the ice fall is calculated above the 40 J energy limits For episodes with an ice load minimum of 1 kg/m the strongest winds during melting were 27 m/s and during ice present 30 m/s for the 35 year period.

Ice cubes (rime ice) with a weight of more than 150 g falling from the mast were considered dangerous, as the impact energy can exceed 40 Joules (see Table 2 and Figure 14). The furthest drift distance for a dangerous ice piece at Tryvann was calculated to be 1.5 times the height of the construction for the strongest wind episode.

The size distribution and fall parameters for the period is presented in Table 2 and we observe with the given discretization in the Cd*A/M parameter that the longest horizontal drift distance is 280 m during the strongest winds (30 m/s), which is 70 m longer than the total mast height. Using the safety distance curve we get 300 m as a safety distance for the worst size ice cube in the 40 J limit.

[1] average density: ρ=500 kg/m^3, freely rotating ice piece[19], Cd*A/M=Cd*(ab+ac+bc)/(2*ρ*a*b*c), where a,b,c are the average side lengths for the ice piece. Cd is taken as 1.0. a=b=c=(L/ ρ)$^{0.5}$

[2] The drag coefficient can vary quite a lot depending on the shape of an object. For flow across a long straight cylinder the drag coefficient is 1.2, for a perfect sphere it is 0.5, while it for cubes varies between 1.05 for flow against a face and 0.8 for flow oriented against an edge. For oblong boxes it can be 2.05 for flow on a face and 1.55 for flow oriented against an edge.

D. Validation and verification of the model

During the winter of 2013-2014, the telecom mast experienced extreme icing conditions and both the mast and area surrounding the mast were inspected. Based on the inspections we consider the model as qualitatively validated yielding zones for ice fall with a high degree of accuracy. A quantitative comparison between the number of ice pieces and larger craters found on the ground in given areas against the calculated probability maps was also found favourable with a logarithmic decrease in the number of strikes per square meter with distance. The kinetic energy of impact is an important parameter in the risk assessment; this could however not be directly compared.

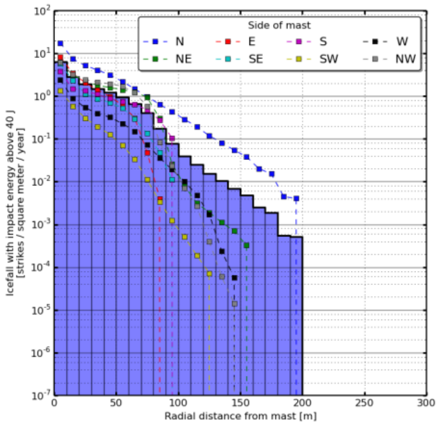

Figure 3: Probability map [#/per square meter] showing combined numbers of ice strikes (E>40J) for each size class together with combined statistics on radial distribution of dangerous ice fall for the 2013-2014 winter. The blue bars show the statistics for all sectors combined, while the colored markers are averages for 8 sectors relative to the mast center described in the legend. (N is north side etc.)

For the ice cube classes with weights of 4 kg, 1.2 kg, 500 g, 250 g, and 150 g the respective furthest drift distance for this winter was calculated to 99 m, 128 m, 156 m, 179 m, and 199 m. The calculated number of dangerous ice fall strikes for the 2013-2014 winter were 3 times of the average for the 1979-2013 period. The calculated mass for the dangerous ice fall was 6 times larger. Both 160 m north of the mast and in the intersection 90 m northwest of the mast the calculated probability for a dangerous strike is 0.02. This corresponds to 1 dangerous strike every 50th m^2.

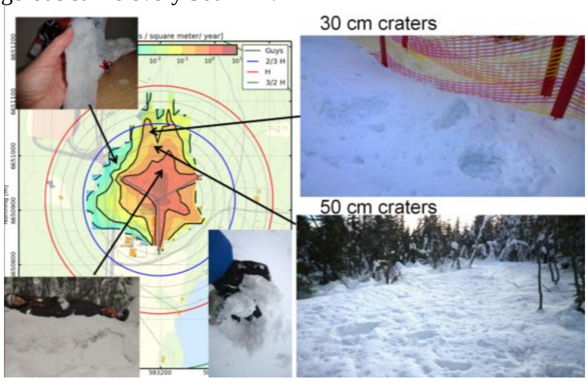

Figure 4: Probability map [#/per square meter] showing combined numbers of ice strikes (E>40J) for each size class together with pictures showing ice fall of different sizes (craters and ice pieces) and probabilities (# craters/ice pieces). The probabilities are based on a simulation for the winter 2013-2014.

The largest ice amount accumulated in the construction this winter was shed in one melting episode with simulated southerly winds of 23 m/s in the top of the mast (16-17th of February 2014). After the event 5-20 cm craters could be observed at a distance of 160 m north of the mast (not shown). On a parking lot 140 m north of the mast 30 cm craters (shown) were observed. In a ski track at distances between 80 and 140 m north of the mast the craters were typically between 5 cm (as showers) and 70 cm (fewer). The 50 cm craters 100 m north of the mast compares with the furthest calculated drift distance for the 4 kg (20 cm) ice cubes while the 30 cm craters at 120 m distance compares with 1.2 kg (13.3 cm) ice cube drift distances. The 500 g (10 cm), 250 g (8 cm) ice cube distributions can both reach the roof of the building at 160 m distance. The 150 g (7 cm) ice cubes reached the 40 J limit only for the strong wind episode yielding a band starting 70 m north of the mast extending to 200 m north of the mast.

Both pictures on the left are from another episode on the 11.02.2014. The coffin hole has a horizontal size of (2m x 1m). The ice piece shown in the upper left of the figure was from a 3 m long section evidently from a guy because of metal thread cast on the inside. It was split in half along the length direction, with a diameter of ~5 cm, and with a density of 800 kg/m3.

E. Forecast system and observations of ice fall as a thin plate

A warning system, coupled to automated forecasts of risk zones for the following 48 hours, was installed before the winter 2014-2015. A total of 6 separate cases with dangerous amounts of ice were forecasted during the winter, which resulted in warnings issued. After each episode, inspections were performed before the warning system was de-activated.

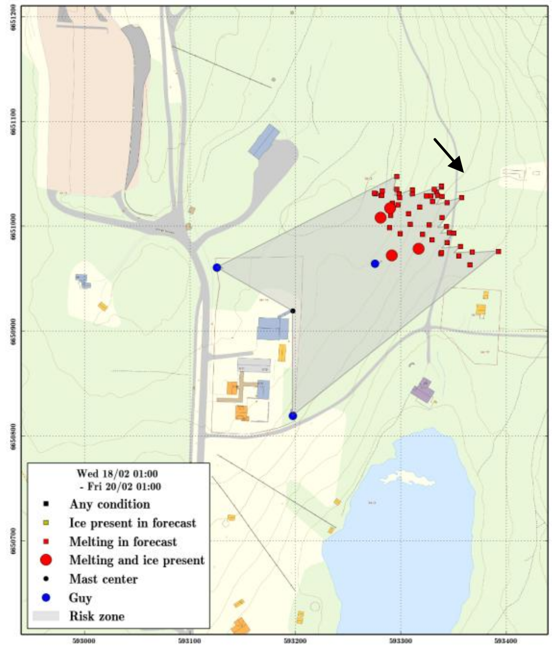

Figure 5: Forecast showing the forecasted risk zone and the safety distance function evaluated for hourly values of wind speed and direction in the 48 hours forecast assuming flat terrain. The red large circles show the combination of melting at the top of the mast when dangerous ice mounts still are present. The smaller red squares indicate positive temperatures for hours after the model has shed the dangerous ice amounts (The closest shown safety distance of 203 m was forecasted for a later time in the same day.

In one of the inspections (2015-02-18 10:00 UTC) observations were made of a large thin plate the size of a news paper that was shed from the glass-fibre reinforced plastics (GRP) top antenna, which is shaped as a 20 m high cylinder in the upper part of the mast with a diameter of 1.6 m. The observed landing position was 210 m northeast of the mast at a terrain height 20 m lower than the mast. At the time of the inspection the modeled wind speed at 209 m were 20 m/s (corresponding to a safety distance for freely rotating ice cubes of 185 m for flat terrain). With a calculated safety distance of 185+20=205 m for the 500 kg/m^3 density freely rotating ice cube safety distance this agrees well with the observed distance of 210 m.

Figure 6: Icefall as 1 cm thin plate (22 cm x 38.5 cm) shed from the round top antenna of diameter 1.6 m. Picture by Amundsen, K., Norkring.

Calculating for the densities of 900 and 800 kg/m^3 we get horizontal drift distances for the regular ice piece of 220-234 m, weights of 680 g-760 g and impact kinetic energies of 130-160 J corresponding to an impact velocity of 20 m/s (72km/h). The same ice piece shedded from the lowest possible position in the top antenna yields a drift distance of 192-204 m for the respective densities assuming flat terrain. These results suggest that the safety distance for freely rotating plates, which are formed from frozen water film on rounder objects such as wind turbine blades and GRP antennas, could be revised and extended with up to 10-20 % depending on future observations. However, at this time we still consider the presented safety distance as valid (ref section B).

IV. ICETHROW FROM WIND TURBINES

For wind turbines, IceRisk calculates the impact position and impact energy of the ice pieces released from various positions on the blades. Heavier ice pieces can be thrown further than light pieces, however light pieces may drift longer distances in strong winds. When ice that has built up on a turbine blade is released it can be thrown hundreds of meters in the worst cases. Calculations with the IceRisk model suggest that safety distances are dependent on the local wind conditions and may in the worst cases with modern turbines exceed the general rule of 1.5 * (H+D), where H is hub height and D is the rotor diameter [11]. If the turbine is located at an elevated position compared to the surrounding, we also recommend adding the overheight, dZ, to H in the above formula for screening purposes.

For the global average in-cloud icing conditions [39] ice accretes at a rate of roughly 1 kg/m/hour on a typical wind turbine blade airfoil section at 85 % blade span for wind speeds of 7 m/s corresponding to a airfoil section velocity of 60 m/s.

F. Calculated ice throw from a V112 3.3 MW coastal wind farm in Northern Norway

For wind turbines the longest safety distances are associated with ice throw of larger ice pieces and not necessarily the drift distance for the smallest dangerous ice piece with the furthest drift distance in strong winds. For ice throw the longest safety distances are related to the performance curves of the turbine, showing peak wing tip velocity during iced conditions [14], and the maximum ice accumulation (e.g. [35][36][37][38]) as larger ice pieces can be thrown further than smaller ones.

The considered turbine has a hub height of 80 m, a rotor diameter of 112 m, and a peak rotational velocity of 17.7 rpm corresponding to a peak wing tip velocity of 103.8 m/s for 25 m/s winds. The considered site is classified as an IEA Wind Ice Class 3 site [15] with light to moderate icing. Expected production losses due to icing for sites in the class is between 3 and 12 %. The highest iceload on a standard body (vertical rotating cylinder with a diameter of 30 mm) is for a 15 year period calculated to 3.4 kg for the considered location varying between 1 and 4.7 kg/m for the turbines in the farm. Based on the ice map for Norway [20] the considered site has between 350 and 550 hours per year with meteorological icing 80 m.a.g.l.

The ice accumulation on the blades have for this site been calculated, using the IceLoss model calibrated against observed ice throw from another operational Norwegian wind farm with similar icing conditions, resulting in the ice throw distribution shown in Figure 7. For an average year the turbine throws 6 000 kg with ice. The highest modelled ice accretion at 75 % of the blade length measured from the hub is 27 kg/m for the 15 year period.

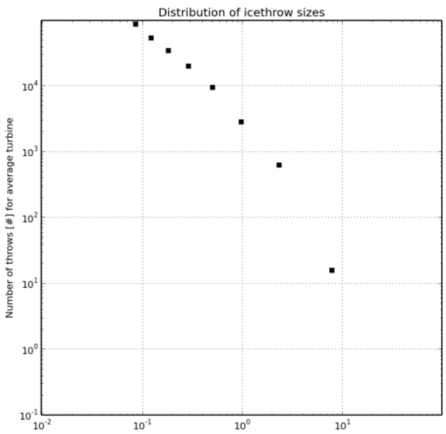

Figure 7 Calculated ice throw size distribution for a 15 year period from 3 blades on a turbine. Number of throws are given in the range of 10^{-1} - 10^5 and sizes in the range of 10 g - 100 kg.

For the considered turbine and location we see from Figure 15 that the calculated ice throw zone extends to 330 m but with most of the ice throw within the general safety distance of 294 m. Smaller ice pieces than shown are not considered harmful while larger ice pieces are considered unrealistic at the given location. We note that the largest and most dangerous ice pieces can be thrown furthest to the side while the lightest ice pieces can drift furthest downwind.

When the wind speed is 30 m/s at the hub height the turbine will stop and the furthest drift distance for this wind velocity is shown in blue with a distance of 220 m in Figure 15. Another general safety rule for a stopped turbine states that the safety distance for ice fall is linear with the wind speed and corresponds to the total height of the construction when the hub wind speed is 15 m/s. Utilizing this rule we get a safety distance of 280 m for ice fall which can be reduced with 20 % to match our results for the longest drift distance for a dangerous ice cube during 30 m/s winds. However, for ice pieces shaped as plates and rods the drift distance is a little higher than for the ice cube in the 40 J limit. Also note that if the stopped turbine is kept oriented against the wind with one blade pointing downward the total height is reduced with another 20 % compared to when one blade is oriented upwards.

The resulting probability distribution calculated with the trajectory model is shown in Figure 8 on a logarithmic scale. Of the 6 000 kg/year of ice thrown we end up with 800 dangerous ice pieces being thrown for the average year from the turbine (E>40 J and M>0.1kg). We observe that the dangerous ice throw occurs within 330 m from the turbine and that the expected return period for at dangerous ice throw on a square meter in the 290-300 m distance range on average is 2 500 000 years. At distances of 150, 75, and 25 m from the turbine the corresponding return periods are 1000, 100, and 10 years respectively for the dangerous ice throw.

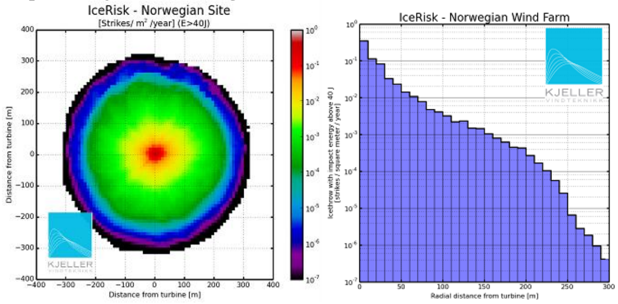

Figure 8: Probabilities for ice throw [strike / square meter/ year] with impact kinetic energy above 40 J from a wind turbine plotted on a logarithmic scale from 10^{-0} to 10^{-7} as a function of distance [m]. The spatial distribution in a 400 m zone around the turbine is shown to the left while the average radial distribution is shown to the right for distances up to 300 m from the turbine. The safety distance using the generic formula is 294 m for this site [8].

G. *Comparison with other studies of ice throw*

In a comparison between thrown ice pieces and ice loads on a standard body [13] (here located at hub height) at the TechnoCentre éolien in Canada indicates that only small ice fragments can accrete on the blade when the ice load on a standard body is below 500 g/m for a REpower MM92 CCV Turbine with hub height of 80 m and rotor diameter of 92 m [16]. The furthest observed throw distance for this turbine is 100 m [8] and the safety distance from the general formula is 258 m. The longest documented icethrow (92 m) relative to the safety distance (135 m) is from Gütch [7]. The furthest observed ice throw known to the author of 140 m is from the EU-project Icethrower[3] for a Vestas V90 turbine with a hub height 100 m. The largest found ice weights are 0.4-0.9 kg but only for a few occurrences. The correlation between distance and wind speed was weak, but the hub wind speed was in the range 9-15 m/s for the observation periods.

A comparison of the IceRisk throw zones for the V90 turbine, using similar figures such as those presented in Figure 15, confirms 140 m as a likely throw distance for 15 m/s winds and an ice cube of size 10 cm (600 g).

3 Preliminary information from project manager Bengt Göransson, Pöyry, from Swedish Energy Agency research project Icethrower (29.08.2014).

V. WET SNOW ICING ON 420 KV POWER LINES CROSSING A NORWEGIAN FJORD

In Norway, crossing fjord spans can have length scales in the order of kilometers with corresponding elevations hundreds of meters above the ground. On these power lines wet snow can accrete for a narrow temperature region around 0 °C [40][41] [42].

For the IceRisk analyses the fjord affected wind field has to be modeled with care because of the steep terrain surrounding the fjord. The horizontal displacement of conductors under wind loading toward buildings etc. should also be considered as well as the line sag. The effect of Joule-heating from the conductor is also being considered in an ongoing analysis as it may play a role for the shed time and the maximum wet snow accumulation.

H. *Terrain model: drift distance above steep terrain*

In Figure 9 a directional sensitivity analysis is performed for a 200 g ice cube released during 200 m winds of 20 m/s. This wind speed corresponds roughly to the highest winds occurring in combination with concurrent wet snow icing for this site during the analysis period. As seen from the figure, the horizontal drift distances for the indicated release position vary between 120 and 240 m depending on the wind direction.

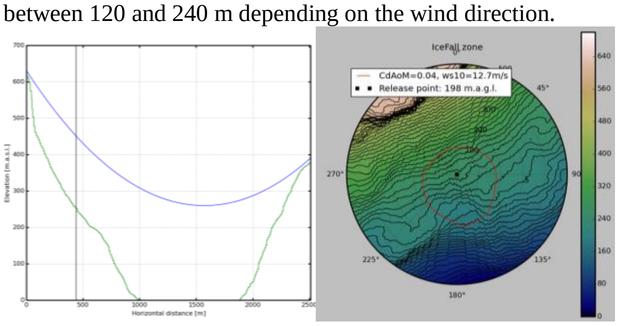

Figure 9: Left: 2.5 km fjord crossing span (blue) above terrain between 0-740 m.a.s.l. (green). The considered position is shown with the black vertical line. Right: Ice piece landing position (red) in 500 m radial zone for different wind directions given indicated release position (black square). 10 m wind speeds are 12.7 m/s, the form factor is CdAoM=0.04 and the terrain is given as black contour with an equidistance of 10 m and corresponding colors in the range 0-700 m.a.s.l.

I. *On the lower limit ice load for a dangerous ice piece and the associated uncertainties*

In the presented analysis wet snow accretions on 6 cm electric conductors crossing a fjord is considered where the 50 year return period ice load is 3 kg/m corresponding to an ice coat with a radial thickness of 2.5 cm. The typical ice densities for wet snow at this site is between 350 and 500 kg/m^3 with increasing density with load.

For this site we observe that snow accretions above a chosen threshold of 1.75 kg/m are rare (5-10 year event). The combination of low ice loads and lack of community experience on icefall from power lines, and the large uncertainly in the size distribution of the falling ice debris, make the IceRisk analyses especially sensitive for this site. Other key questions are on the ice amounts that can shed without breaking, on the limiting thickness and length for a falling rod before the dynamic pressure exerted will erode and break the debris into smaller pieces. As the wet snow accretion events are associated with positive temperatures it is also a key question if the ice has time to freeze before it is shed. We are currently working on improving the wet snow modeling which includes ice erosion and shedding as part of an ongoing research project with Statnett as a partner (FRonTLINES). In the current model setup, ice is assumed to shed within 24 hours after the active icing event or when the wet bulb temperature of the snow reaches 2 °C whichever comes first. We also expect the modeled ice load at this site to be conservative and that it can be reduced with model improvements [43][44][45][46][47][48][49][50][51][52].

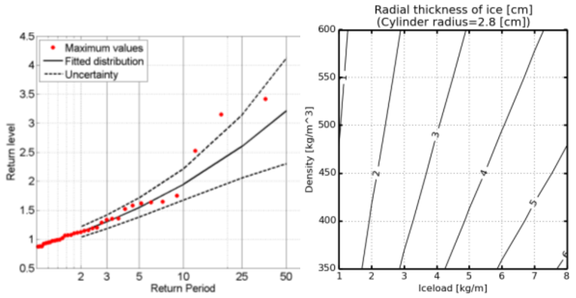

Figure 10: Return period [years] for wet snow ice load [kg/m] on conductor (left) and the relation between density and radial thickness as function of ice load (right).

VI. Risk assessment

J. Relation between impact kinetic energy for an ice piece and probability of survival

From [18] the relation between impact kinetic energy and fatality for debris (weight between 100 g and 4.5 kg) thrown from explosions are given. The relation is based on a probit function matching skull-base fracture criteria for fragments with weights between 0.1 and 4.5 kg. For debris between 100 g and 4.5 kg, thrown from explosions the 1%, 50 % and 99 % probabilities of death are matched to the kinetic energies of 46, 71 and 110 J.

For the impact kinetic energy of 40 J, the probability of survival is evaluated to 99.9 % [18]. Since the band between certain death and 40 J is narrow, we have in our analyses mainly assumed 40 J as a sharp limit between dangerous (fatal) and non dangerous ice pieces [2][4]. With an ice density of 500 kg/m^3, the 40 J limit compares roughly to 200 g of ice falling from 30-50 m or 500 g of ice falling from 5-6 m for freely rotating ice cubes. If a 500 g freely rotating ice cube of size 10x10x10cm (500g) reaches terminal velocity of 23 m/s (given by Cd*A/M=0.03), the impact kinetic energy will be above 120 J. Evaluating the risk function we get that the probability of survival is 81.7 % for 60 J, 26 % for 80 J, and 0.25 % for an impact kinetic energy of 120 J.

K. Guidelines for acceptable risk levels

Currently there are no internationally recognized standards for safety distances or methods for assessing the risk caused by ice fall or ice throw. Guidelines, rules and regulations vary significantly by country [5].

Lloyd's Register Consulting has proposed safety zones around wind turbines, met masts, towers and similar installations that may case risk of ice throw or ice fall [2], based on Norwegian Directorate for Civil Protection (DSB) guidelines for acceptable risk outside industrial facilities [17]. The result is a map showing safety zones, i.e. what type of activities are acceptable within the vicinity of the wind turbine or similar installation.

The key guiding principle for determining safety zones is that the facility should not increase risk to public significantly compared to daily risk in society.

Exposure time is factored into the acceptance criteria, resulting in different zones for different type of activities. A zone with low activity, will have a higher risk acceptance criteria than a zone with high public activity. Higher risk may also be accepted for personnel operating the facility, when taking into account that this will be professional personnel with understanding, knowledge, and routines to handle the risk.

L. Suggested risk acceptance criteria

Guidelines for acceptable risk level, both for personnel operating the facility and third parties, are proposed and shown in Figure 10. The calculated risk for any specific site may take into account local risk reducing measures, and calculate individual risk for different exposure, such as pedestrians and vehicle passengers, separately [26][27].

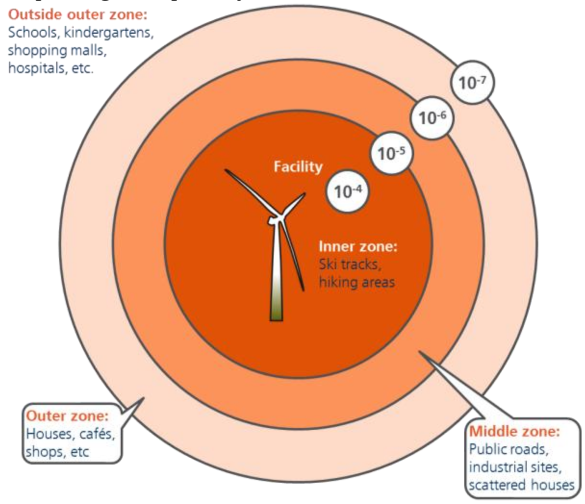

Figure 11: Lloyd's Register Consulting's suggested safety zones around installation that may case risk of ice throw or ice fall. The numbers indicate the iso-risk contours for localised individual risk (LIRA), the probability that an average unprotected person, permanently present at a specified location, is killed during one year due to ice fall or throw from the facility.

Lloyd's Register Consulting's suggested safety zones and acceptance criteria for localized individual risk (LIRA) is in line with the IEA Task 19's suggestion [3]. While IEA Task 19 suggests a general approach based on the ALARP principle (As Low As Reasonably Practicable), Lloyd's Register Consulting propose more detailed limits, and acceptable activity within each safety zone.

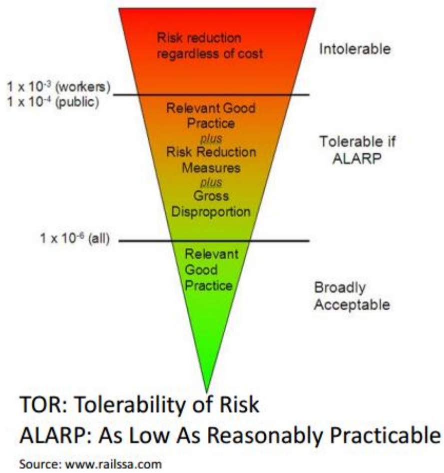

Figure 12: Risk reduction according to the ALARP principle as presented by IEA Task 19 suggestion [3].

The principle of minimising impact on the surroundings and risks imposed by the facility, is a common denominator in most international guidelines and regulations. In cases where there are no clear guidelines or rules regulating the dangers associated with ice fall and ice throw, it rests on the installation owner to document safe operation. In for example UK, there are strict requirements to document that risks are acceptable according to the ALARP principle [33].

To put the risks of fatality due to ice fall or ice throw in perspective, in line with the key principle that the facility should not increase the risk to public significantly, we can compare to the risk of fatality from any accident in Norway ($3.7 * 10^{-4}$), and the top three risks: Fall accident ($1.6 * 10^{-4}$), transportation excl. railway ($6.5 * 10^{-5}$), and poisoning ($3.6 * 10^{-5}$) [34]. The total increase in risk due to risk posed by the facility (from ice fall, ice throw or anything else) should be negligible compared to these figures.

M. Localised individual risk (LIRA)

LIRA is the probability that an average unprotected person, permanently present at a specified location, is killed in a period of one year due to an accident at a hazardous installation [31]. The term corresponds to individual risk as presented in [17].

For evaluating the risk we are considering a person, of size 20 cm x 50 cm = 0.1 m^2, standing permanently at a fixed position. Assuming that all strikes with impact energy above 40 J as 100 % fatal. The LIRA statistic is found by dividing the probability of strike per square meter with impact energy above 40 J per year with 10.

N. Risk assessment for the 209 m telecom mast at Tryvann, Oslo

If we apply the Lloyd's Register Consulting's suggested safety zones, for a third person of size 0.1 m^2 standing permanently in a fixed position, on the LIRA statistic for Tryvann shown in we get the following distances for the respective inner, middle, outer, and outside outer safety zones:

-Ski tracks and footpaths	110-200 m from mast
-Public roads and scattered houses	135-235 m from mast
-Cafe, ski lifts, and houses	170-260 m from mast
-Kindergarden	260 m from mast

The safety limit for allowing a person walking along the road (middle safety zone) is then at a 190 distance west of the mast (220 m south-west).

In addition to risk for pedestrians at Tryvann we have also analyzed the risk for car drivers and passengers on the road 80 m west of the mast [26][27]. With the assumption that[4] applies to cars in general it was found that the roof construction can withstand even the largest ice piece that can reach the road at Tryvann, which is a 4 kg cube with an impact kinetic energy below 2700 J. Since the impact angle for ice pieces hitting the road 80 m from the mast was calculated to be 70 degrees to the horizontal the weak side windows were not considered further in the analysis. However, 10 % of the cars projected horizontal area consist of laminated front windows[5], which are designed to stand impacts[6] of up to 140 J. The relation between LIRA and strike probability above the given energy limit for a car driver was combined to 0.01. Strikes on the rear window were not considered in the analysis.

At Tryvann the calculated risk for car drivers was not within the 140 J limit, but if the energy for penetrating the window (140 J) was added to the limit for fatality for an unprotected person of (40 J), then the calculated risk was equal to the combined alternative accept criteria of 180 J for the road.

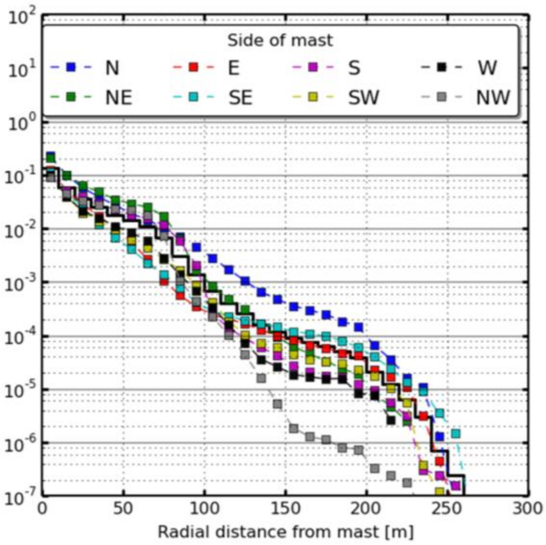

Figure 13 Localized individual risk calculated for the period 1979-2013. [1/year] assuming flat terrain. The black line shows the all-sector average in radial intervals of 10 m. The colored lines shows averages for the sectors described in the legend. Since terrain wasn't not included in the calculations we recommend subtracting the overheight for the lookup distances when there is overheight between the mast location and the considered area.

O. ISO 12494 indicate 2/3 structure height as the maximum distance for falling ice in R6 rime ice class (Tryvann)

The ISO-12494 – Atmospheric Icing of Structures Rime classes are [13]: R1: 0.5 kg/m, R2: 0.9, R3:1.6, R4:2.8, R5:5.0, R6: 8.9, R7: 16, R8: 28, R9:50 kg/m as 50 years return ice mass 10 m.a.g.l. on a standard body.

For Tryvann the 50-year iceload is 10 kg/m [24] at the 10 m level corresponding to ice class R6. The indicated [13] maximum distance for falling ice is at 2/3 of the structure height. We note that the standard remarks on the large uncertainty associated with the indicated safety distance.

[4] An American study [28] has shown that cars that are tested according to the NHTSA compliance program can stand a load on the roof corresponding to 1.5 times the cars dry weight in a simulated roll-over.

[5] A typical automobile covers a horizontal area of 6-7 m^2 (1.5 m wide x 4.2 m long = 6.3 m^2). The front window is typically 1.5 m wide and 0.7 m high with a 30 degree angle to the horizontal (projection of 0.42) covers a horizontal projected area of 0.63 m^2.

[6] The minimum energy required for a steel ball of 2.25 kg to break and penetrate a laminated wind screen was 138.6 J [29]. Firstly, we note that the 140 J limits for dangerous ice fall is conservative since steel (and concrete) are denser than ice and therefore smaller objects in these materials have a higher penetration ability. Secondly, the probability for ice crushing is larger than for the other materials. Hence, the area for spreading the impact kinetic energy is larger for ice.

Table 1: ISO 12494 indicated maximum distance given ice class and structure height (h). The presented risk are calculated at the given distances for 209 m mast at Tryvann (Oslo), which is in the Ice class R6. The DSB safety zone class is given to the right for the indicated distances.

ISO Ice class	ISO maximum distance	All sector risk	Risk north sector	DSB average zone	DSB zone north sector
R0-R3, G0-G1	Normally not considered				
R4-R6, G2-G3	2/3h (140m)	$1x10^{-4}$	$7x10^{-4}$	Touching inner limit inner zone	Inside inner limit inner zone
R7-R8, G4-G5	H (210m)	$2x10^{-5}$	$1x10^{-4}$	Middle zone	Touching inner limit inner zone
R9-R10	3/2h (315m)	$<10^{-7}$	$<10^{-7}$	Outside outer zone	Outside outer zone

P. *Risk assessment for the wind turbine*

The outer safety zones where housing is accepted is at the 10^{-5} contour and is located on average 250 m from the turbine (280 m away on east side; not shown) . Since the projected size of a person is 0.2 m x 0.5 m and all strikes with an impact kinetic energy above 40 J is considered fatal this corresponds to the 10^{-6} [1/year] LIRA contour. The inner safety zones where ski tracks and hiking areas are excepted is on average located 150 m from the turbine (10^{-3} strikes/year/m^2). The middle safety zone is on average located 230 m from the considered turbine. (public roads etc.).

VII. Examples with icicles from rooftops, hydrometeors (hail), and icefall from bridges

In an urban environment icicles falling from poorly insulated roofs have caused injuries in Norway[7] and fatalities in other countries[8]. In Norway landlords are responsible for clearing ice and court has ruled that owners are liable for damages.

In rare violent hailstorms, Large hail (2-2.75") reach the 40 J limit for sizes between eggs and tennisballs (5.1-6.4 cm, Cd=0.65, rho=700-910 kg/m^3 [53]).[9] The largest hailstone recorded fell in Vivian, South Dakota on July 30, 2010. It measured 8" in diameter (20 cm), 18.5" in circumference (47 cm), and weighed almost 2 pounds (880 g). Hail stones of this size are extremely rare. A hailstorm in the Moradabad and Beheri districts of India killed 246 people on April 30, 1888, the deadliest hailstorm on record in modern history[10].

In Vancouver, Canada, the newly built Port Mann bridge had a design flaw leading to formation of large ice pieces directly above the traffic lanes.[11]

[7] http://www.newsinenglish.no/2011/07/07/icicles-led-to-injury-and-prison-term/

[8] Falling icicles have killed five and injured 150 people in St Petersburg following Russia's coldest winter in three decades. Regional figures show icicles kill dozens of Russians each year. http://www.telegraph.co.uk/news/worldnews/europe/russia/7512865/Falling-icicles-kill-record-numbers-in-St-Petersburg.html)

[9] http://www.washingtonpost.com/posttv/national/severe-thunderstorms-hail-strike-denver-area/2015/06/04/9f1fd370-0ac0-11e5-951e-8e15090d64ae_video.html

[10] http://www.dailymail.co.uk/news/article-2271147/Nine-people-killed-freak-hailstorm-rains-massive-boulders-Indian-villages.html#ixzz3c8fYSDzt

[11] http://www.news1130.com/2014/12/22/port-mann-bridge-ready-to-tackle-ice-bombs-ti-corp

VIII. Summary

A trajectory model is used together with the energy limit of 40 J to differentiate dangerous ice throw or fall from other ice debris. Safety zones based on calculated risks are suggested based on similar criteria for other industries. For the icefall from the Tryvann communication mast we assumed freely rotating ice cubes of density 500 kg/m^3 where the length of the ice piece (l) in each class is dimensioned after the accreted ice load (L) and density (rho), $l = (L/rho)^{0.5}$

Based on current observations of differently shaped ice pieces with varying densities the safety distances calculated for the freely rotating ice cube holds and we consider the calculated ice fall risk zones as highly accurate.

For ice throw, the safety zones have been calculated using a density of 800 kg/m^3 since denser ice pieces can be thrown further than lighter ones and ice gets denser when accreted at high speeds which is the case for a moving turbine blade.

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Table 2 Statistics on dangerous icefall for the period 1979-2013 released from mast and guy positions in Tryvann telecom mast, Oslo. Note that the Cd*A/M parameter is increased with 50 % for a freely rotating ice cube compared to an ice cube falling with the flat side oriented against the wind and falling direction. The drag coefficient, Cd, is taken as 1.0. Note that the given terminal velocities and impact kinetic energies are valid for calm wind conditions are therefore taken as lower limits for the falling ice pieces. In the IceRisk calculation, the contribution to the kinetic energy from the horizontal ice piece velocity is included. With the wind conditions at Tryvann the smallest ice piece with impact kinetic energy above 40 J is 7 cm weighing 150 g.

Ice cube size [m]	Ice cube weight [kg]	Terminal velocity [m/s]	Kinetic energy at terminal velocity [J]	Cd*A/M [m^2/kg]	Maximum distance [m]	Ice fall with energy > 40 J [cubes/year]	Ice fall with energy > 40 J [kg/year]
0.050	0.063	16.3	8	0.040*1.5	(329)	-	-
0.057	0.093	17.5	14	0.035*1.5	(307)	-	-
0.067	0.148	18.9	26	0.030*1.5	283	80	12
0.080	0.256	20.7	55	0.025*1.5	256	4902	1255
0.100	0.500	23.1	133	0.020*1.5	225	2495	1247
0.133	1.185	26.7	422	0.015*1.5	188	936	1110
0.200	4.000	32.7	2136	0.010*1.5	142	151	603
Sum						**8566**	**4227**

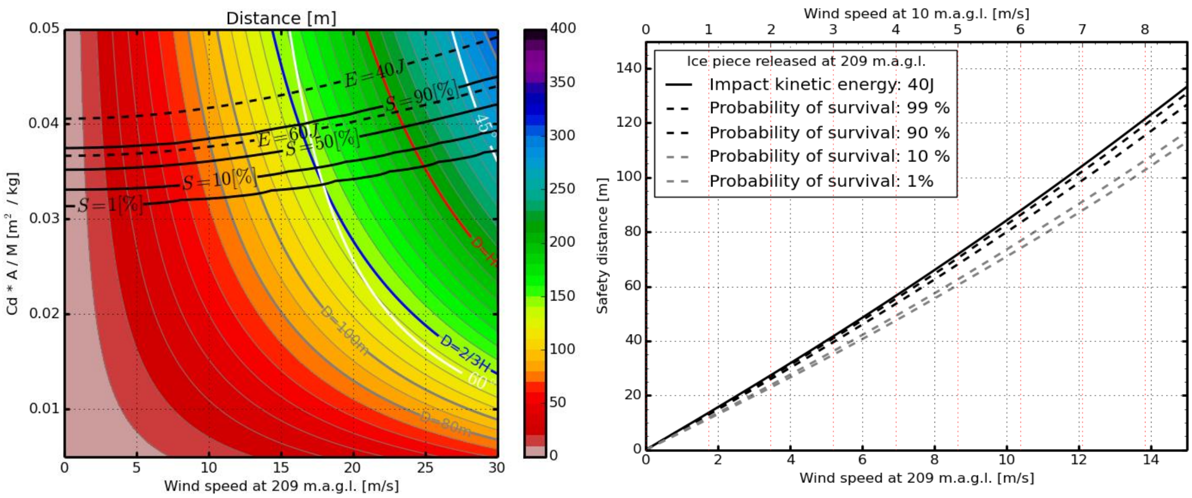
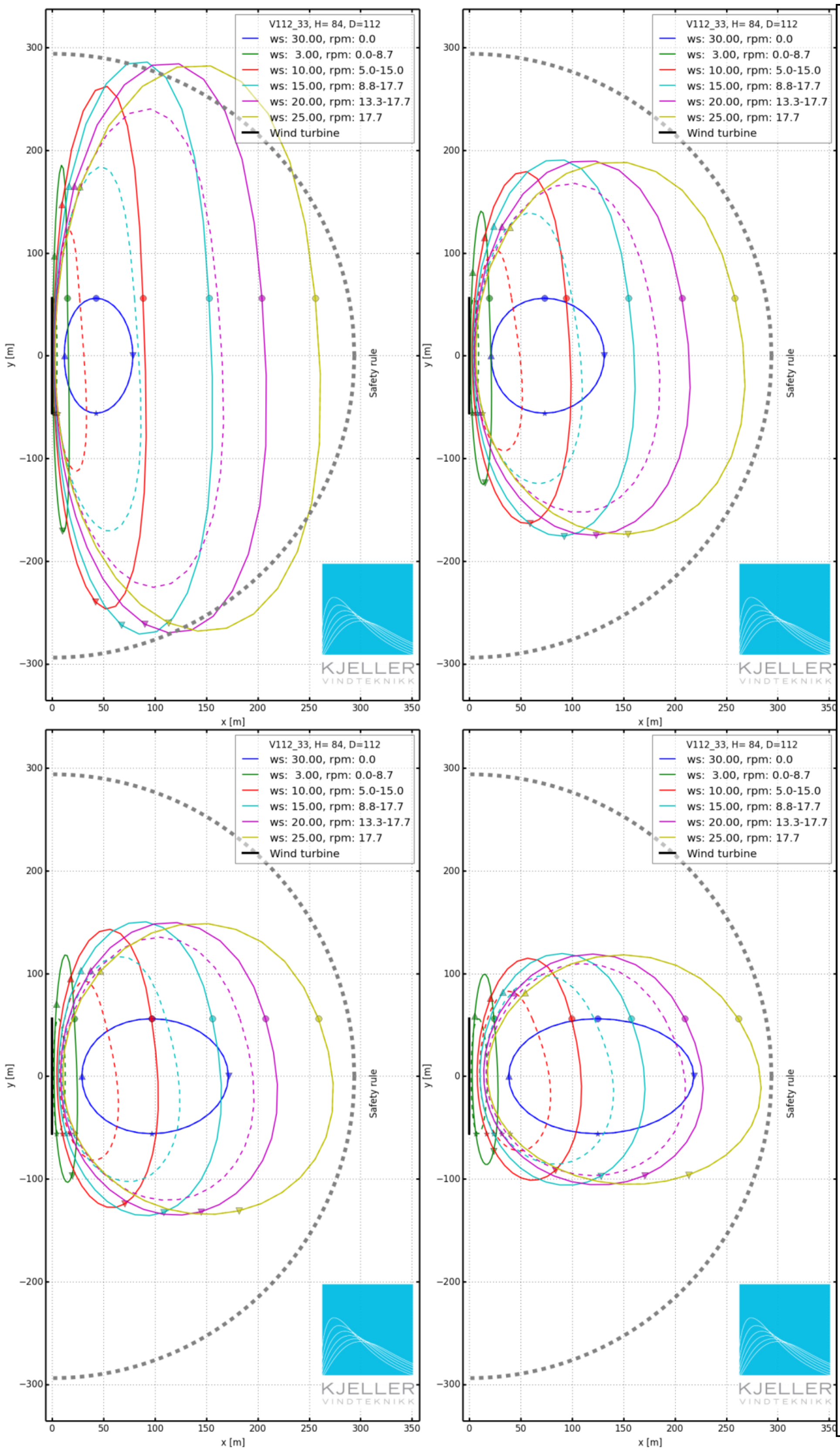


Figure 14: Left: Distances for impact of icefall released at 209 m.a.g.l.. The parameters that dimension the ice fall distances are the drag-coefficient (Cd), the effective frontal area of an ice piece (A) and the weight of the ice piece (M) in addition to the wind speed and shear. A wind shear coefficient alpha=0.18 is used based on a high resolution simulation of the local wind condition. Freely rotating ice cubes with a density of 500 kg/m^3 and a drag-coefficient of 1 is used in the presented results. The distances that correspond to the mast height of 209 m, as well as 2/3 of this height is marked as thicker red and blue lines. The distances of 80 and 100 m is marked by thicker grey lines to ease the reading. The dashed black lines shows the greatest distances freely rotating ice cubes with impact kinetic energies of 40 and 60 J can drift at the given wind velocities. The solid black lines shows the probability of surving (S) being hit by the ice piece given impact kinetic energy and mass (assuming all energy is trasfered on impact). The levels of 90, 50, 10 and, 1 % probability of surving impact of the smallest ice cube with sufficient impact energy (the worst case) is given. The white lines shows the impact angles relative to the ground. (60° and 45°). **Right:** Safety distance for smallest ice cubes (worst case with size depending on wind speed) reaching the impact kinetic energy limit of 40 J. The ice cubes are released from the top of the construction as function of given windspeed at 10 m and 209 m heights (x-axis above and below). The safety distance curve (40J) is nonlinear and can be fitted with the following representation: D = A+B*C*(exp(WS/B)-1). Here WS is the wind velocity at 209 m, A=-3.4, B=63.5 , C=8.1, and D is the safety distance.



The wind direction is from left to right and the black line shows the turbine position and extent viewed from above (positive z-direction). The ice throw zones for 4 different ice piece sizes are shown in 4 separate plots with in order of decreasing size and weight for regular ice cubes. The blue circles shows the ice fall distance from a stopped turbine during hub wind speed of 30 m/s. The full lines shows where the ice cubes that are thrown from the wind tip will land when turbine is operating without performance reduction giving lowered rpm at given velocities. The dashed lines shows corresponding ice throw zones when icing has caused a performance reduction due to the icing. The rpm values and wind speed are shown in the legend. The markers shows the release orientation and directional movement of the blade (the blade moves along the +y-axis at the lowest position (shown with the upward triangle marker). The gray dashed line shows the general safety distance rule: (H+D)*3/2 (294 m) [8].. Red, light blue, purple and yellow colors shows the ice throw zones when the hub velocity is respectively 10, 15, 20 and 25 m/s. For an ice density of 800 kg/m^3 the icethrow zones shown in the 4 figures correspond to ice cubes of sizes 5 kg (19 cm), 600 g (10 cm), 200 g (6 cm) and 60 g (4 cm). For an ice density of 500 kg/m^3 the ice throw zones corresponds to ice cubes with respective sizes of 13.5 kg (30 cm), 1.7 kg (cm), 500 g (10 cm), og 150 g (6.7 cm). Since flat terrain is assumed in this calculation ice pieces can be thrown a longer distance if there is overheight between the turbine position and the surroundings.

Figure 15: Calculated ice throw zones for different ice piece sizes thrown from the wing tip of a Vestas V112 - 3.3 MW turbine. This turbine has a rotor diamater of 112 m and a hub height of 84 m.